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Exploration Requirements Development Utilizing the Strategy-to-Task-to-Technology Development Approach

Bret G. Drake and B. Kent Joosten
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, TX

Donald W. Monell
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

The Vision for Space Exploration provides direction for the National Aeronautics and Space Administration to embark on a robust space exploration program that will advance the Nation's scientific, security, and economic interests. This plan calls for a progressive expansion of human capabilities beyond low earth orbit seeking to answer profound scientific and philosophical questions while responding to discoveries along the way. In addition, the Vision articulates the strategy for developing the revolutionary new technologies and capabilities required for the future exploration of the solar system. The National Aeronautics and Space Administration faces new challenges in successfully implementing the Vision. In order to implement a sustained and affordable exploration endeavor it is vital for NASA to do business differently. This paper provides an overview of the strategy-to-task-to-technology process being used by NASA's Exploration Systems Mission Directorate to develop the requirements and system acquisition details necessary for implementing a sustainable exploration vision.

THE VISION FOR SPACE EXPLORATION

On January 14, 2004 the President of the United States articulated a new Vision for Space Exploration[1]. This vision calls for a progressive expansion of human capabilities beyond low earth orbit seeking to answer profound scientific and philosophical questions while responding to discoveries along the way. This vision sets forth goals of: returning the Space Shuttle safely to flight; completing the International Space Station (ISS); retiring the Space Shuttle when the ISS is complete; sending precursor robotic orbiters and landers to the Moon; sending human expeditions to the Moon, conducting robotic missions to Mars in preparation for a future human expedition; and conducting robotic exploration across the solar system. In addition, the Vision articulates the strategy for developing the revolutionary new technologies and capabilities required for the future exploration of the solar system. This vision specifically calls for: 1) Implementation of a sustained and affordable human and robotic program to explore the solar system and beyond; 2) Extending human presence across the solar system, starting with a human return to the Moon no later than the year 2020, in preparation for human exploration of Mars and other destinations; 3) Developing the innovative technologies, knowledge, and infrastructures to support human and robotic exploration; and 4) Promoting international and commercial participation in exploration to further U.S. scientific, security, and economic interests.[2] This vision represents a bold new step for the Nation, and the National Aeronautics and Space Administration.

NASA faces new challenges in successfully implementing the Vision as articulated by the President. The Exploration Systems Mission Directorate within

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NASA headquarters has been charged to provide the leadership role in enabling the Vision for Space Exploration[3]. In order to implement a sustained and affordable exploration endeavor it is vital for NASA to do business differently. In 1986 President Ronald Reagan established a blue ribbon commission on defense management, known as the Packard Commission, to focus on understanding ways to reduce inefficiencies in the defense procurement system[4]. The commission concluded that the primary problems with the acquisition process were the same ones identified in previous decades, namely cost growth, schedule delays, performance shortfalls. As NASA moves forward with implementation of the Vision, emphasis must be placed on doing business differently, specifically:

- Get the operator and technologist together to enable leveraging cost-performance trades.
- Apply technology to lower the cost of the system, not just to increase the performance.
- Adequately mature technology prior to engineering and manufacturing development.
- Ensure the solutions are mutual and agreed upon between technologists and operators.
- Instigate and catalogue acquisition reform.
- Teamwork: Operating under the principal of teamwork where the government and industry work together in a true integrated product team.
- Best practices: Incorporating sound ideas for improvement in each acquisition using streamlined methods such as Broad Area Announcements when appropriate and the used of streamlined electronic submittal and source selection processes.

THE SPIRAL DEVELOPMENT APPROACH

Affordable and sustainable implementation of the Vision for Space Exploration is being accomplished in what is termed a spiral development approach. In spiral development, the end-state requirements are not known at program initiation. Those requirements are refined through system development and demonstration, risk management and continuous user feedback. The spiral development approach builds on the experience gained in early spirals to provide flexibility in responding to scientific discoveries and to incorporate new technologies into future spirals. The process for formulating and prioritizing requirements gathers engineers, scientists, operators, and astronauts together to craft a well-defined statement of mission objectives derived from Agency exploration goals and policy and budgetary priorities. Examples of the first few spirals associated with the initial exploration capabilities, including lunar exploration, are defined as:

Spiral 1 establishes the capability to test and checkout crew transportation system elements in Low Earth Orbit in preparation for future human exploration missions to the Moon. Robotic missions that are necessary for gathering environmental data and proving technologies and concepts in support of future human missions are also included in this spiral.

Spiral 2 establishes the capability to conduct human exploration missions on the surface of the Moon for extended durations. In this context, extended duration is defined as the capability to support the crew on the surface of the Moon for a period greater that what was accomplished during the Apollo missions. Systems necessary to satisfy Spiral 2 objectives consist of the Spiral 1 elements, or derivatives of those elements, plus systems necessary to transport elements to the lunar vicinity as well as providing the capability for the crew to access the lunar surface. Focused robotic precursor technology demonstration missions to Mars are also anticipated within this spiral.

Spiral 3 establishes the capability to conduct routine human long duration missions on the surface of the Moon to test out technologies and operational techniques for expanding the human presence to Mars and beyond. Missions in Spiral 3 will extend in duration from those conducted in Spiral 2 up to several months in duration in order to serve as an operational analog of future Mars missions. The Spiral 3 phase requires the development and deployment of additional surface systems necessary to support the crew for the long duration missions.

Spiral 4 and beyond includes humans missions to Mars and other destinations. Details associated with these future spirals less defined at this time, but will continue to be refined as analysis and additional strategic planning is conducted.

STRATEGY-TO-TASK-TO-TECHNOLOGY

The strategy-to-task-to-technology process involves the coordination of an integrated team of users and developers in the requirements generation process[5].

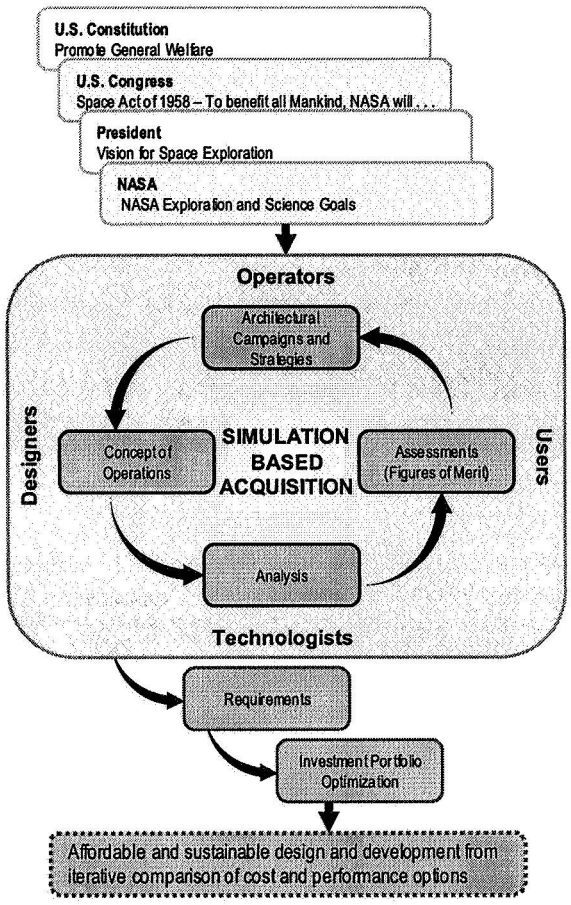

Figure 1 Strategy-to-Task-to-Technology Process.

Identification and assessment of user-defined future operational needs is essential in determining which technologies and demonstrations will be pursued and funded. The strategy-to-task-to-technology process serves as the critical link among the requirements community, the technology community, and the eventual acquisition program office, while focusing on reducing both cost and risk of technology, process, and concepts to meet future operational needs and affordability.

Using a rigorous, facilitated process, the requirements formulators along with the operators (Operational Advisory Group) and government and industry technical experts, execute a top-down strategy-to-task approach to requirements definition (Figure 1). This process leads the team from basic founding principles, such as the 1958 Space Act, to the Vision for Space Exploration, to specific operational tasks. This effort produces a credible, auditable trail of the decision-making process.

Integral to this activity is the examination of solutions in a simulation based modeling environment to address deficiencies in accomplishing operational tasks. The baseline campaign results provide robust deficiencies analysis, required features, and benchmark for future evaluation of contractor concepts for the exploration program. Exploiting modeling and simulation in this way will support the creation of an affordable exploration approach.

Quality Functional Deployment efforts within the strategy-to-task-to-technology process explicitly links exploration technology projects to the derived deficiencies and thus to the exploration system elements and strategies. Rigorous cost-performance trade study analyses are vital prior to defining the exploration program investment plans. Each technology maturation project requires a cost-performance trade study, a life-cycle cost perspective, and an operational objective in the strategy-to-task process. The technology maturation results are available to all exploration system contractor teams, not just to those that perform technology work. This innovative approach works for both the government and industry teams, even in a highly competitive program environment.

APPLICATION OF STRATEGY-TO-TASK-TO-TECHNOLOGY FOR EXPLORATION

NASA's Exploration Systems Mission Directorate is currently employing the strategy-to-task-to-technology (STT) process in the execution of the Vision for Space Exploration. The Vision for Space Exploration is less than a year old, and thus the development of the specifics of the strategy-to-task-to-technology process are still being formulated. The following discussion provides an overview of the current strategy-to-task-to-technology approach being formulated within the Exploration Systems Mission Directorate. The STT process is being implemented in a phased approach such that lessons learned from the initial implementations can be incorporated into further refinement of the process.

ARCHITECTURE CAMPAIGNS AND STRATEGIES

A key step in execution of the strategy-to-task-to-technology approach is the development of strategic campaigns that represent a range of potential approaches for implementing the Vision. Strategic campaigns, often referred to as "architectures", are derived directly from the governing policy guidance as shown in Figure 1. Understanding key strategic

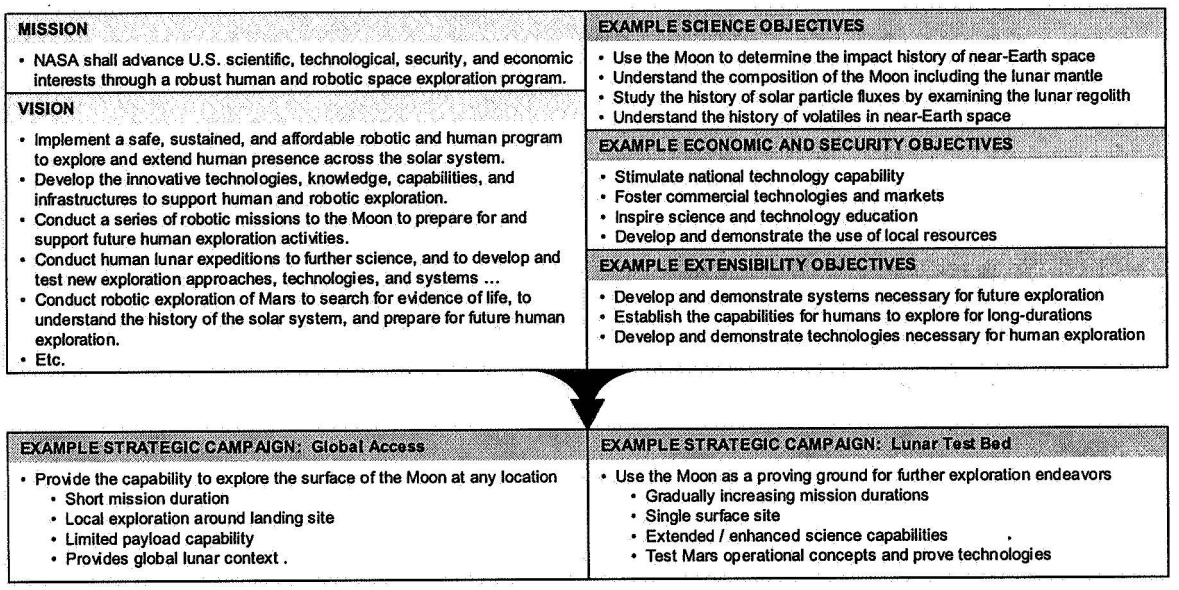

Figure 2 Defining Strategic Campaigns.

objectives and stakeholders' needs and expectations is essential in developing systems and elements which collectively can be used as part of a system-of-systems, or "super-system", for implementation. Specific campaigns and strategies are developed to meet the expectations, or collection of expectations of stakeholders. The strategic campaigns are used as the basis for system decomposition to further define potential systems, elements, and necessary technologies needed for successful implementation of the Vision. Example strategic objectives as derived from the Vision are shown in Figure 2. As can be seen from this figure, the Vision for Space Exploration, as articulated by the President, sets general policy and is very broad in nature. There are numerous ways in which the Vision can be implemented, but which should take precedence over the other? For instance, should more emphasis be placed on developing the capability to land anywhere on the Moon to conduct scientific investigations, or should a single outpost be emplaced to serve as a test bed for future operational approaches and technologies? Decomposing the Vision into specific strategic objectives allows the requirements team to establish a series of implementation baselines from which comparisons can be made. Each strategic campaign emphasizes certain aspects of stakeholders needs. In addition, each strategic campaign can be used to develop the overall operational concept and specific tasks necessary for implementation of that campaign.

CONCEPT OF OPERATIONS

Operations concepts provide a user oriented description of the operation of one or more system elements in support of the architecture. Operational concepts provide a specific detailed description of the operational performance of the system in conducting the overall mission. The Operations Concept answers the following types of questions:

- In what environments are the systems expected to operate?
- How will the systems accomplish the mission objectives?
- What are the critical system parameters to accomplish missions?
- How effective or efficient must the systems be when performing missions?
- How long will the systems be in use?

The concepts of operations describe, in terms understandable to the space, scientific, developmental and lay communities, how specific elements will be used to implement the Vision. It is intended to initiate dialogue between the requirements and development communities to frame issues and identify areas for trade studies. The concept of operations is a source document for use by NASA, as well as a means to convey operational principles to external communities and vendors. Internal to NASA, the concept of operations provides traceability for internal NASA tracking of requirements development and generation as well as providing to other NASA directorates and NASA field centers insight into the goals and objec-

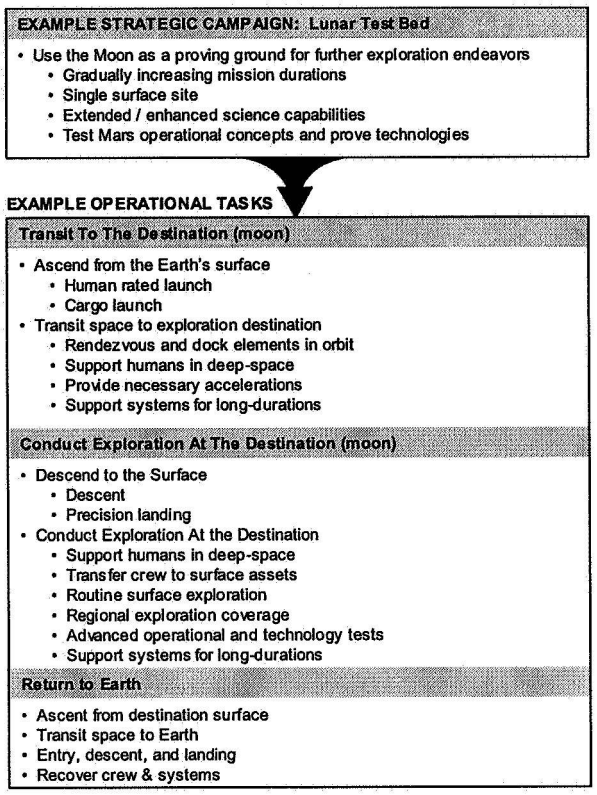

Figure 3 Operational Concept Tasks.

tives driving the system designs as part of the implementation of the Vision. Externally, the concept of operations serves as a vehicle to provide a common understanding for other government agencies, industry partners and academia as well as providing a conceptual baseline to assist Congress in its oversight responsibilities. The concept of operations can be decomposed to lower levels of fidelity in order to establish basic tasks that must be performed. For example, the capability to support humans in deep-space requires that protective measures be devised to ensure crew health and maximize mission success as humans including radiation protection, zero-g countermeasures, remote medical care, advanced life support systems, to name a few. These challenges related to human support are subsequently used to drive systems designs and ultimately technology development guided by the strategy-to-task-to-technology process.

ANALYSIS OF DESIRED CAPABILITIES

Throughout the requirements definition process analysis is conducted in order to determine appropriate functional requirements including allocation of those requirements to the appropriate exploration systems. In order to determine the appropriate functional requirements including their impact on overall affordability and risk, trade studies must be performed. The strategic architectural campaigns described earlier are used as the mission baseline for performing the studies. Established figures of merit are used to compare alternative mission and technological approaches.

The process of functional decomposition is used to develop further definition of how the various systems comprising the overall architecture work together to accomplish the overall mission. Decomposing the system into lower level detailed descriptions provides the necessary definition to determine the specific functional requirements of the elements and resulting interfaces between elements. Through this process the various elements are decomposed into lower-level sub-functions. This process is continued until the system is decomposed into its basic sub-functions and each sub-function at the lowest level is completely and uniquely defined by its requirements. Through this process, analyses of trades at the system, subsystem, and technology arenas are performed consistent with the figures of merit. An example of the flow down is shown in Figure 4. As mentioned, developers and users together conduct the operational simulations and participate in the trade studies to address key systems features and characteristics.

After the functions have been completely decomposed, it is possible to identify and document the requirements, functional and physical interfaces between elements of the system including both internal interfaces and external interfaces with items outside of the system of interest.

FIGURES OF MERIT

Figures of merit are used by the Exploration Systems Mission Directorate to ensure that strategic investments are properly aligned to implement the Vision of Space Exploration. The figures of merit are used to measure the benefit of one approach as compared to other alternatives within a decision model. Utilizing a standard, consistent set of measures makes it possible to compare alternatives in addition to providing insight into the performance sensitivities of the alternatives and variations due to different assumptions and inputs. Assessments of technology choices must be made within the context of specific mission concepts being considered. The following figures of merit are applicable to the Exploration Systems Mission Directorate requirements formulation and technology investment activities.

Safety and Mission Success: Measures of effectiveness associated with safety and mission success focus on determining the degree to which a mission concept or technology option ensures safety and reliability for all mission phases. To be sustainable, future space exploration systems and infrastructure, and missions pursued using them, must be reliable, and when astronauts are involved, they must be as safe as reasonably achievable. Emphasis is placed on understanding comparative values of safety-related measures of performance discussed below:

Risks: Risk assessments include an assessment of the events that could result in loss of crew, loss of vehicle, and mission failure. This includes assessments of the degree to which the mission concept or technology allows for simple interfaces within or between elements. This also includes an assessment of the number and complexity of the associated interfaces.

Hazards: An assessment of the mission and technology risks which have the potential to cause a mishap. This includes hardware, software, and operational issues that could result in loss of crew, personnel, vehicle, or mission.

Aborts: An assessment of the ability of the mission concept or technology choice to provide for survival of the crew during various mission phases due to anomalies that result in early mission termination. Aborts could include early vehicle return or safe havens, but must result in safe return of the crew to Earth.

Redundancy: An assessment of the design features which will allow for the safe crew return in the event of a system failure which otherwise would be catastrophic. Design redundancy should consider both redundancies within a system and between elements, as well as the ability of the system or technology to provide functional redundancy from dissimilar means.

Reliability: An assessment of the probability that a mission concept or technology choice will successfully complete the desired mission, along with a confidence factor based on available data and model maturity.

Contingencies: An evaluation of the technology or mission operations concepts that are not the primary methods of accomplishing a function, but used for mission success or crew safety. For example crew manual action required to overcome a docking system failure to allow demating of two elements.

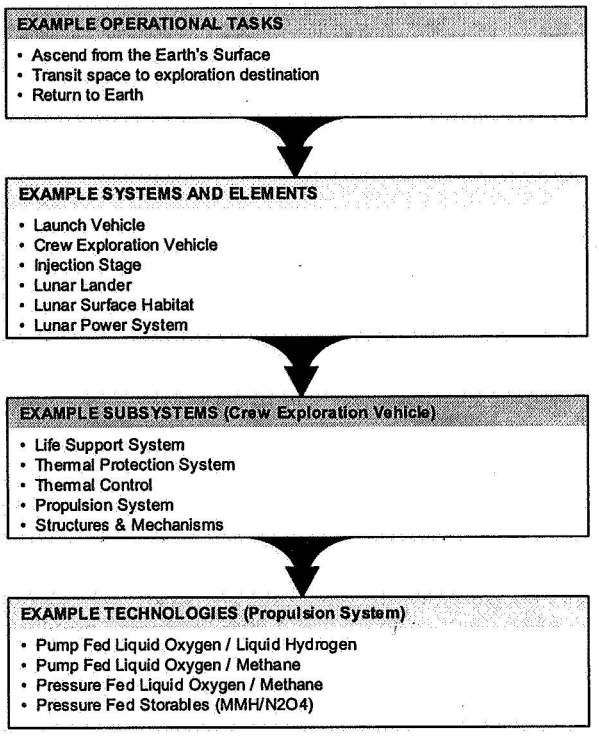

Figure 4 Functional Decomposition.

Effectiveness: Measures of performance associated with effectiveness focus on determining the degree to which the mission concept, or technology option, effectively meet mission needs. Future space exploration systems and missions must be effective. In other words, the capabilities of a new system or infrastructure must be worth the cost and risk of developing, building, and owning them. The goals and objectives achieved by the missions using those systems and infrastructures must be worth the cost and risk involved in operating them. Effectiveness must be determined case-by-case, based on the specific design features of the system or infrastructure, and based on the detailed mission objectives (e.g. science objectives) that may be achieved.

Mission Objectives: Assessment of capability of the mission approach or technology choice to satisfy exploration objectives.

Mass: Total mass required to be delivered to low-Earth orbit to support initial mission (includes pre-deployed infrastructure, if any) and the required mass for each subsequent mission. Also includes an assessment of the total number of launches required to emplace the necessary infrastructure as well as for each recurring mission.

Extensibility: Measures of effectiveness associated with extensibility focus on determining the degree to which the technology, subsystem, or system options effectively meet future mission needs.

Elements: Applicability of the elements, for example Crew Exploration Vehicle, lander, habitat, EVA suit, surface power, in meeting future mission needs.

Subsystems: Applicability of subsystems, for example life support system, in-space propulsion system, power, in meeting future mission needs.

Technologies: Applicability of specific technologies in meeting future mission needs.

National Security: Ability of the concept or technology to enhance national security from a strategic or economic perspective should be addressed.

Commercialization: This measure focuses on the degree to which the proposed concept or technology enhances or opens new commercial markets and opportunities. Examples of commercialization include technology transfer, infrastructure emplacement followed by future privatization, and creation of new commercial markets or products, etc.

Affordability: To be sustainable, future space exploration systems, infrastructures, and the missions pursued using them must be affordable. In other words, the costs for design, development, test and engineering for the systems must be consistent with projected future year NASA budgets. (The same is true for the recurring costs of additional copies of all exploration systems). Similarly, the costs associated with operating these systems in future space exploration missions must be consistent with projected future year NASA budgets. Assessments of affordability include the degree in which the proposed mission or technology option is expected to provide an affordable approach. Assessments in this focus area include both total expected costs as well as affordability assessments regarding expected funding profiles and phasing.

Development: Total cost for the design, development, test and evaluation of the required systems and facilities that constitute the element or mission concept under consideration, including that required to mature technologies at a TRL of 6 or greater.

Recurring: Total annual program, infrastructure, and facility costs necessary for execution of the mission concept (e.g. sustaining engineering, hardware production, ground and mission operations, etc.), assuming a predefined flight rate.

Marginal: This includes additional cost necessary to execute one additional flight for the subject element or mission concept under consideration (e.g. hardware production, ground and mission operations, etc.).

Technology: Total costs required to advance the technology to a TRL level of 6.

Availability: An assessment of effort and associated risk required to bring the required technologies to TRL 6 by six years prior to initial operational capability date (9 years for technology that affects the overall system of systems) and includes assessments of the effort and associated risk to develop required elements and supporting infrastructure within the required schedule.

SIMULATION BASED ACQUISITION

Trade study and system design analyses which support the decision making process are conducted within an integrated Simulation Based Acquisition (SBA) environment. Simulation based acquisition involves the application of new capabilities, such as virtual environments and advanced modeling languages. Early, ongoing and evolving modeling and simulation of systems and their environments is used to enable users, technologists, designers and operators to make informed decisions on architectures, missions and concept designs. An integral part of the strategy-to-task-to-technology process is the application of these simulation based acquisition capabilities to provide a quantifiable assessment of the impacts,

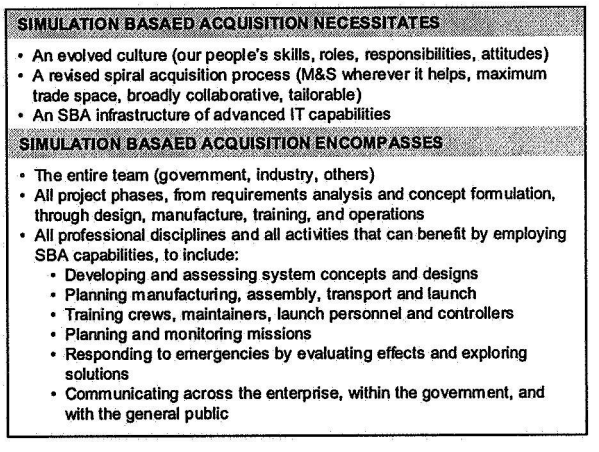

Figure 5 Simulation Based Acquisition Characteris-

or benefits, of alternative operations concepts and design capabilities as they are applied to the exploration systems.

Analytical models that represent architectures, concepts-of-operations and the corresponding systems are developed based upon an understanding of the exploration strategies and available technologies. As was mentioned earlier, the strategy-to-task-to-technology process is being implemented in a phased approach. The SBA models initially take the form of low-fidelity mathematical representations (e.g., spreadsheets) of the concepts but evolve over time into high-fidelity physics-based representations (e.g., finite element models, etc.) of the systems. Regardless of the level of fidelity, the system is represented in the areas of performance, cost and risk, enabling the assessment of the Figures-of-Merit that provide a measure of goodness of the concept. Through an iterative process, the models are refined to the point of accurately representing a reference concept. This is the analytical point of reference that will be used to compare alternative technologies and changes in the concept of operations.

The "rosetta stone" for the integrated modeling and simulation capability is the NASA Exploration Information Ontology Model (NExIOM). The purpose of the NExIOM is to capture, describe and preserve decision support information regarding exploration architectures and technologies. The NExIOM will encompass architectures that span in maturity from conceptual to operational. NExIOM content will serve as the sole expression of architecture and technology data for the purposes of proposal submission, engineering analysis, modeling, simulation, assessment, reporting and decision-making. Data will be accessible to NASA for the purposes of retrieval, evaluation, analysis and review of analysis data. Stored information will also be accessible to industry for the purposes of submission and retrieval of analysis data, with the ultimate vision to constitute the sole repository for all data that drives any analysis, model or simulation in support of the exploration systems decision-making process.

As technologies are improved or new technologies evolve, the technology community provides updates to the parameters used to describe the technology in the model. Working with the technology organization, the model and/or simulation will be modified by the analysts to reflect that change and then "re-run" to assess the changes in figures of merit. Note that single technologies or suites of technologies are modeled. Additionally, changes in the concept-of-operation will also be modeled in order to assess the impacts on the figures of merit.

Executed properly, simulation based acquisition will foster better informed, timelier and more defensible decisions throughout the acquisition life cycle. By so doing, SBA will improve the quality of our systems and speed their development, at less cost and risk than would otherwise be the case.

PORTFOLIO INVESTMENT OPTIMIZATION

A key element of the strategy-to-task-to-technology process is the generation of the information necessary to support prioritization and decision making processes. The simulation based acquisition process provides fundamental assessment data consistent with the figures of merit. These data can then be used to perform decision analysis including enabling the ability to prioritize investments. This process generates best value portfolio investment strategies that can be aligned with the near, mid and long term requirements consistent with the spiral development approach. Establishing a "best practice" decision methodology uses the agreed upon criteria (figures of merit) to select optimal alternatives at key points in the process. Key stakeholders, including the operators and users, are active participants in the process that builds a shared understanding of objectives and value drivers. Developing a repeatable analysis and decision data generation process can significantly reduce decision cycle time while at the same time provide a traceable, defensible investment strategy for internal and external stakeholder review.

Techniques used for measuring the benefits of various design solutions and technologies are not straightforward due to the inherent complexity of human exploration missions. Although total mission mass, specifically the mass savings from the application of a specific technology, has been used as the first order measure of benefit, all figures of merit must be included in the decision making process. The measured value of a specific technology is highly dependent on the interrelationship of it in concert with other applied technologies, which we term "technology bundling"[6]. For instance, the value of an advanced technology as applied to a mission model comprised of "today's" technologies will provide more benefit than applying that same technology to a mission model comprised of "tomorrow's" technologies. Implementation of the strategy-to-task-to-technology process, in combination with simulation based acquisition analysis capabilities, provides a repeatable, measurable process of evaluating the benefits of technologies in implementation of the Vision.

Providing the capability to optimize the allocation of scarce resources (Figure 6) based on specific strategic

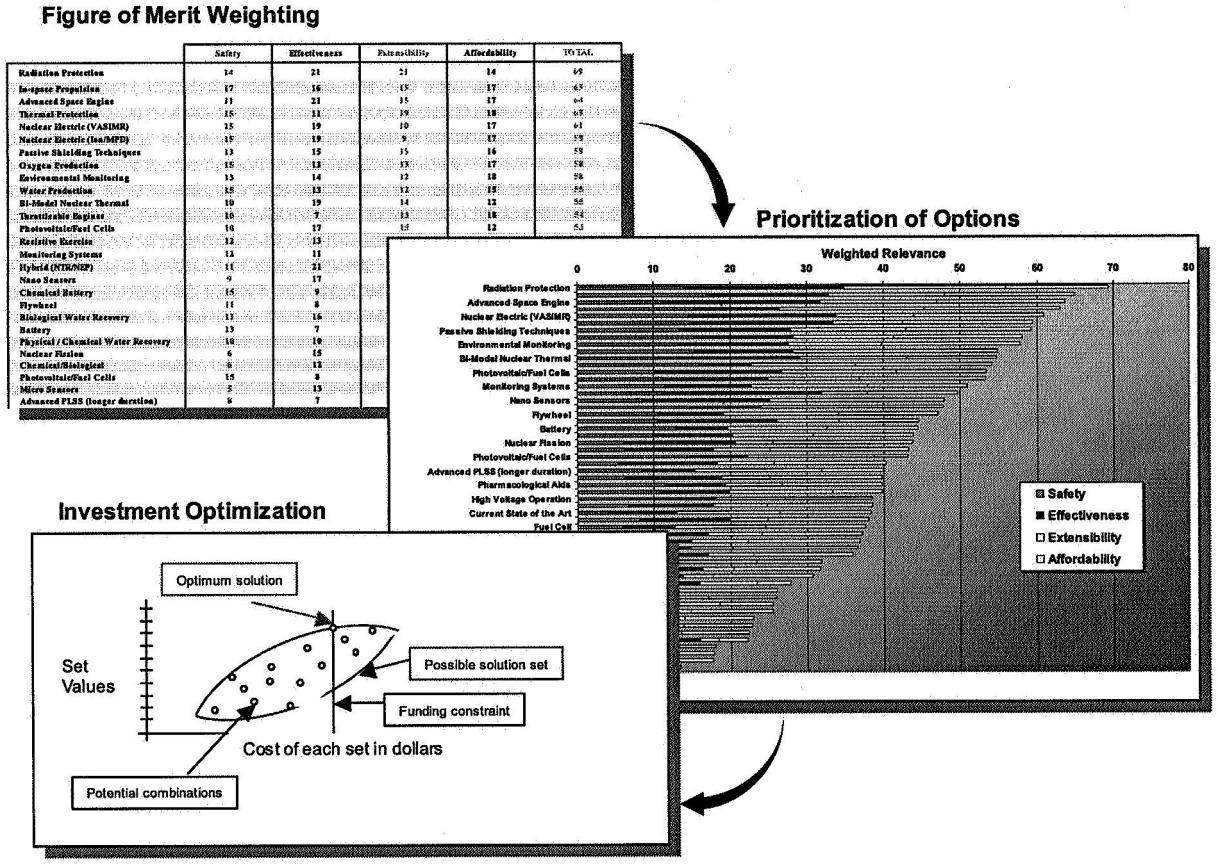

Figure 6 Example Investment Portfolio Optimization.

needs ensures a smooth technology pipeline to time-phased requirements. In addition, insight provided by the process maximizes management flexibility allowing the exploitation of new opportunities, termination of low value efforts and the ability to react to changes in policy. The portfolio investment optimization process allows iteration over time to re-balance the allocation and application of resources.

CONCLUSION

The government and industry team is converging on exploration architectures and initial strategies for implementing the Vision for Space Exploration. The exploration community is continuing to refine and advance the technologies and mission approaches needed to support future human exploration missions. The primary goal of these efforts is to develop mission architectures, including technology options, which can significantly reduce the cost and risk of human exploration. During the technology development planning process, emphasis is being placed on those approaches that can provide a sustainable exploration approach providing the most leverage in terms of risk and cost reduction. The strategy-to-task-to-technology process is a fundamental element in implementing the Vision and it will continue to evolve as the exploration endeavor progresses

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[1] "A Renewed Spirit of Discovery," Remarks by the President of the United States, January 14, 2004.

[2] "The Vision for Space Exploration," National Aeronautics and Space Administration Headquarters, NP-2004-01-334-HQ, February 2004.

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[6] Drake, Bret G., et al, "Technologies for Human Space Exploration: Earth's Neighborhood and Beyond," AIAA-2001-4634, AIAA Space 2001 Conference and Exposition, Albuquerque, New Mexico, 28 - 30 Aug 2001.